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diction has been found between the spectroscopic and the trigonometric results. This is the more remarkable since we should expect occasional idiosyncracies in the spectra of stars subject to exceptional physical conditions, and the rareness of such cases is interesting evidence for the uniformity of the development of stellar spectra in general.

RELATION OF COLOR TO INTRINSIC LUMINOSITY IN STARS OF THE SAME SPECTRAL TYPE

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It has long been known that the color of a star is intimately related to its spectral type. More recently it has been found that color is also correlated with intrinsic brightness.[1] Thus, two stars having different luminosities, but the same spectrum so far as the usual criteria are concerned, may differ in color-index by more than half a magnitude.[2]

The phenomenon is perhaps to be accounted for as follows: Similarity in spectrum implies at least approximate equality in surface brightness. Difference in luminosity is therefore mainly a matter of size, the brighter object being the larger. But inequality of dimensions doubtless entails differences in atmospheric constitution, and hence also in the selective absorption occurring in the atmospheres. Since color is determined by the distribution of intensity in the continuous spectrum, while type relates more particularly to the characteristics of the spectral lines, one star may thus appear redder or bluer than another, although both are of the same type.

But whatever the explanation, an extension of the results of Adams, van Rhijn, Monk, and others to include a wide range of luminosity for each spectral type is immediately desirable, because of their bearing upon the difficult problem of stellar constitution. Further, any phenomenon correlated with stellar luminosity should be studied to the utmost, on account of its possible importance for the determination of interstellar distances. If the intrinsic brightness of a star can be found, the problem of its parallax is solved.

The method employed for the measurement of color in securing the preliminary results here described is that of exposure-ratios[3], which is convenient and reliable, and much more expeditious than the direct determination of color-index.

An isochromatic plate exposed behind a yellow filter records the intensity of the 'yellow' light received from the star. The same plate used without filter registers the 'blue' light; the longer wave-lengths are then also active, but the image, nevertheless, is essentially blue, owing to the relatively great blue-sensitiveness of the isochromatic plate. In neither case are we dealing with monochromatic light, or even with a very narrow range of color. That, however, is of no great consequence; it is only important that the mean wavelengths for 'blue' and 'yellow' should differ by a considerable amount. The relative intensity for the two spectral regions will then vary with the color of the star, and in consequence may be used as an index of its color.

Practically, however, it is simpler to use as a measure of color the ratio of the exposure times which will yield blue and yellow images of equal intensity, or, better still, the logarithm of this ratio. Thus we make a series of exposures to blue, usually 2^s, 4^s and 8^s, and then one or more to yellow, such that the resulting images fall within the limits of size fixed by the first and last blue exposures. For an early-type star the yellow exposures are generally 32^s and 64^s, for an intermediate type 16^s and 32^s, and for a late type 8^s and 16^s. The logarithm of the exposure-ratio for equal blue and yellow images is then estimated directly from the plate. With a normal emulsion the logarithms for the principal spectral types (ratio of blue to yellow for stars of zero absolute magnitude) are approximately as follows: Bo, 8.79; Ao, 8.94; Fo, 9.10; Go, 9.26; Ko, 9.44; Ma, 9.55.

Troublesome photographic difficulties are avoided by using images of constant size produced by a constant series of exposure times, compensation for differences in apparent magnitude being made by varying the aperture of the telescope. With the 60-inch reflector stars as faint as the eleventh magnitude can be observed with the exposures given above.

The photographic emulsion is changed as infrequently as possible, for every change necessitates a systematic correction, and indeed each plate usually requires a small correction. From five to ten stars are ordinarily observed on each plate; and, since the adopted value for a star is based on several plates, the measures themselves afford a means of reducing the individual plates to a homogeneous standard system of colors.

The measures require a correction for atmospheric extinction, but since all the observations on a plate are made at about the same zenith distance, this is assumed to be constant and is determined as a part of the systematic correction for the plate. Errors depending on seeing and atmospheric conditions generally also enter into the plate correction and are thus largely eliminated from the results.

The internal consistency under favorable conditions is illustrated by the accompanying observations of the two components of 61 Cygni which extend over an interval of about two years. The logarithms of the exposure-ratios for the two stars, which were photographed simultaneously, are in the first two columns of the table. The average deviation of the differences in the third column corresponds to about 0.08 magnitude, which indicates the uncertainty in a single determination of the difference in color of two stars on the same plate. This differential result, which is free from systematic plate-errors, is equivalent to an uncertainty of 0.05 or 0.06 magnitude in one measurement of the color of a single star, a quantity of the same order as the average deviations found directly from the measures of each of the two components, whence we conclude that the plate-errors have been successfully eliminated. The complete observation of a star, including the setting of the telescope, requires seven or eight minutes.

Exposure-ratio—Components of 61 Cygni

LOG R_1	LOG R_2	DIFFERENCES	v_1	v_2	v_3
9.39	9.50	−0.11	+0.03	−0.02	+0.05
9.41	9.47	−0.06	+0.01	+0.01	0.00
9.43	9.45	−0.02	−0.01	+0.03	−0.04
9.39	9.50	−0.11	+0.03	−0.02	+0.05
9.43	9.45	−0.02	−0.01	+0.03	−0.04
9.42	9.48	−0.06	0.00	0.00	0.00
9.42	9.47	−0.05	0.00	+0.01	−0.01
9.42	9.47	−0.05	0.00	+0.01	−0.01
9.44	9.45	−0.01	−0.02	+0.03	−0.05
9.40	9.48	−0.08	+0.02	0.00	+0.02
9.40	9.49	−0.09	+0.02	−0.01	+0.03
9.39	9.50	−0.11	+0.03	−0.02	+0.05
9.41	9.49	−0.08	+0.01	−0.01	+0.02
9.39	9.49	−0.10	+0.03	−0.01	+0.04
9.48	9.51	−0.03	−0.06	−0.03	−0.03
9.44	9.50	−0.06	−0.02	−0.02	0.00
Means 9.416	9.481	−0.065	±0.019	±0.016	±0.028 (log R)
1.09	1.27	−0.18	±0.053	±0.045	±0.078 (magnitude)

Results are now available for about 150 stars whose spectral types and absolute magnitudes have been derived mainly from three sources: the extensive and valuable lists of spectroscopic parallaxes by Adams and Joy, which include types F, G, K, and M;[4] the A stars known to belong to the Taurus Stream;[5] and the B stars whose parallaxes have been determined by Kapteyn.[6]

The weight of the results is very unequal; some of the stars used as standards have been observed a dozen or more times, while for others only a single observation is available. The nature of the correlation between color and luminosity is nevertheless clearly enough indicated, although quantitatively it will be subject to considerable revision.

The discussions thus far undertaken are very simple. The stars having absolute magnitudes between +1 and −1 were separated fom the others and arranged according to spectral type. By plotting spectrum against exposure-ratio a curve was obtained (circles, fig. 1;) which shows the relation of these two factors for stars of zero absolute magnitude. The dwarf stars of the later spectral types, whose mean absolute magnitudes are 6 or fainter, were similarly treated, thus giving the second curve (points) shown in fig. 1.

For $M = 0$ the variation is nearly linear up to K5; but beyond this point there seems to be no further increase in color with advancing spectrum, the latest K's (K6) and the various sub-classes of the M stars all having approximately the same color. Further, the result noted by earlier observers is at once evident, namely, that the giant G and K stars are redder than the dwarfs of the same spectrum. The difference becomes zero for F_5, and is again zero, or at least very small, for the M stars, although the difference in luminosity between the giants and dwarfs is here about 10 magnitudes with a corresponding range in intensity of 1 to 10,000.

For further study of the relation of color to luminosity we consider groups of stars having the same spectral type. As they stand, the data are insufficient; but provisionally we proceed by reducing all the stars within any spectral sub-division to the mean spectrum with the aid of the curves of fig. 1. Thus all the B stars are reduced to B5 by applying to the logarithms of the exposure-ratio of each a small correction which makes the colors very nearly what they would have been had the types actually been B5 throughout. The six groups of results thus obtained have been plotted separately—logarithms of exposure-ratios as ordinates against absolute magnitudes as abscissae—and are shown in figs. 2 and 3.

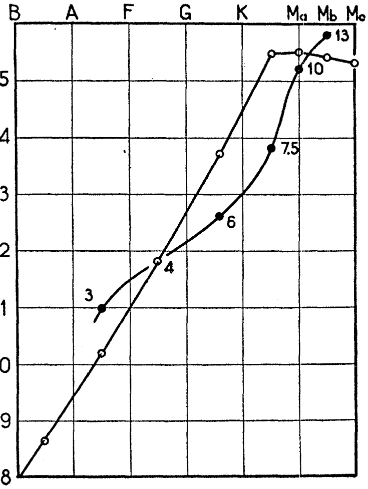

FIG. 1. ORDINATES: COLOR (LOGARITHM OF EXPOSURE-RATIO)
ABSCISSÆ: SPECTRAL TYPE

The open circles represent mean valves for stars of zero absolute magnitude. The dots refer to stars of fainter luminosity, the respective mean absolute magnitudes being indicated by the accompanying figures.

The results for the B stars are to be regarded as altogether provisional. They suggest that the color decreases, that is, becomes bluer, as the intrinsic brightness decreases. The A stars, all of which belong to the Taurus stream, increase in color with increasing absolute magnitude. This result seems definite, and is confirmed by the Fo and F1 stars derived from the lists of Adams and Joy, which are shown by the crosses in fig. 2. When reduced to A5 they agree well with the A stars of the Taurus stream. A further confirmation is found in the fact that these A stars, whose absolute magnitudes, with one exception, lie within the range $M = +1.2$ to $+3.0$, agree with the curve for $M = 0$ determined by the adjacent spectral types (see fig. 1,) only after their colors have been reduced to $M = 0$ in accordance with the relation shown in fig. 2.

The giant and dwarf F stars in the mean have sensibly the same color, but when the individual results are plotted we find pretty definite evidence of a change in color as indicated in fig. 2, first an increase and then a decrease in color with increasing M, the maximum lying somewhere near $M = +2$.

The results for the G's and K's (fig. 3;) are qualitatively certain beyond any question, the giants as before remarked being very much redder than the dwarfs. For the K stars the difference in the corresponding color indicates for $M = -1$ and $+7$ is more than 0.6 magnitude. This large difference is immediately suggestive of the errors that may occur in attempting to infer spectral type from color, or to determine visual magnitude from photographic with the aid of the spectral type, as is not infrequently done.

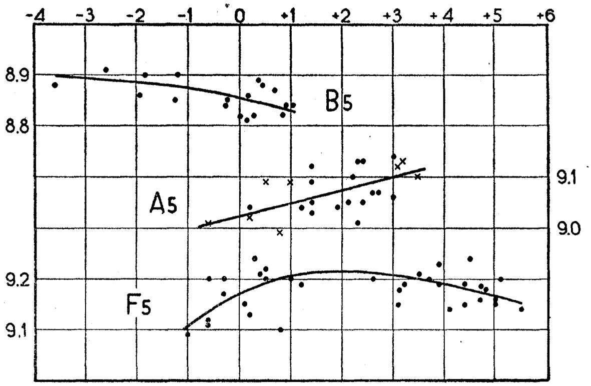

FIG. 2. VARIATION OF COLOR (LOGARITHM OF EXPOSURE-RATIO, AS ORDINATE) WITH ABSOLUTE MAGNITUDE (ABSCISSA) FOR B, A AND F STARS

The points represent individual stars whose colors have been reduced by the curves of Fig. 1 to the mean spectra, B5, A5, etc., for the respective classes. The crosses in the A5 group are F0 and F1 stars reduced to A5.

Among the dwarfs themselves, neither for the G's nor the K's, does there appear to be much change of color, although the faintest K's suggest that a minimum occurs at $M = +7$ and that from there on the color increases with increasing M.

The last curve of fig. 3 illustrates the similarity of color for the giant and dwarf M stars.

In spite of the diversity of the curves, relationships for adjacent spectral classes can usually be traced. Thus the curve for the A stars seems to be related to the ascending branch of that for the F's, while the descending branch of the latter curve reappears in the results for the G's and K's. The behavior of the M's is peculiar, and owing to the lack of late K types the transition cannot certainly be traced. The interrelation of the B and A stars is also open to question. From the present results we should infer that for Ao stars there is little or no dependence of color upon absolute magnitude. This indeed seems to be the case. For example, Vega and the companion to o^2 Eridani, both Ao and differing intrinsically by more than ten magnitudes, are very nearly of the same color.

The change in the relation of color to luminosity from type to type is so rapid that a closer subdivision of the spectral classes is desirable, but this must await the accumulation of further data.

Aside from the bearing of these results upon the problem of stellar constitution, which it would be premature to consider at present, it is perhaps worthy of remark that they may occasionally be useful for determinations of distance Thus in the present case the results afford a useful control on the parallax of the Taurus Stream. As previously mentioned, it is only when reduced to zero absolute magnitude with the aid of the curve for the A5 stars that the colors of the Taurus stars are brought into agreement with the smooth curve for zero absolute magnitude defined by the adjacent spectral types (see fig. 1). Conversely, had the parallax of the Taurus Stream been unknown, it could have determined from the data now available with an indicated uncertainty of about 20 per cent, or ±0".005, which is comparable with the precision of the result usually adopted.

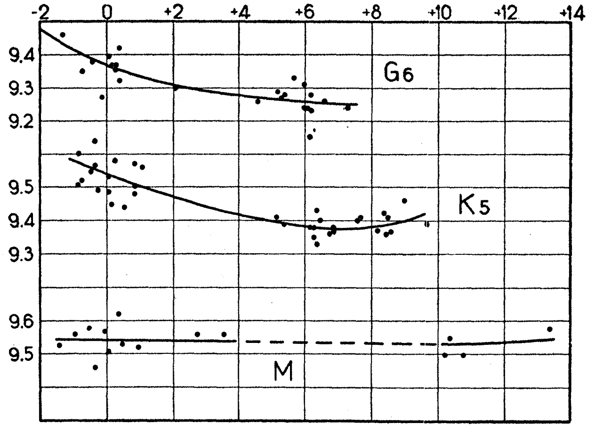

FIG. 3. VARIATION OF COLOR (LOGARITHM OF EXPOSURE-RATIO, AS ORDINATE WITH ABSOLUTE MAGNITUDE (ABSCISSA) FOR G, K, AND M STARS

All the G and K stars have been reduced in color G6 and K5, respectively. Ma. Mb, and Mc stars have been combined without correction for color.

The use of any such method, however, presupposes a knowledge of the spectral types of the stars in question. But if spectra are available, the spectroscopic method of determining distance can immediately be employed; at least this will be true if stars of intermediate or late type are present. The results afforded by observations of color would however be useful as a control on spectroscopic or trigonometric determinations of parallax, although they might not add greatly to our knowledge of stellar distances. But if the method depending on color measurements could be extended in such a way as to obviate the necessity of direct spectral observations, the advance would be of importance, for it could then be applied to faint stars beyond the reach of both trigonometric and spectroscopic methods of measuring distance.

Theoretically such a procedure seems not impossible. Suppose, for example, that we observe three spectral regions instead of two, and that we combine the results in such a way as to yield two exposure-ratios, $\log R\ (\lambda_1, \lambda_2)$ and $\log R\ (\lambda_1, \lambda_3)$, λ_1, λ_2, and λ_3 representing the effective wave-lengths of the three regions in question. Presumably both these quantities would be functions of the spectral type S and the absolute magnitude M; hence, we could write

$$\log R\ (\lambda_1, \lambda_2) = \mathrm{F}_1\ (S, M)$$
$$\log R\ (\lambda_1, \lambda_3) = \mathrm{F}_2\ (S, M)$$

from which it might be possible to determine both S and M, and therefore, finally, the parallax, with the aid of the usual formula

$$5 \log \pi = M - m - 5$$

in which m is the apparent magnitude.

It must be admitted, however, that the trials thus far made hold out no great promise of success, owing to the fact that the coefficients in the two equations involving S and M are so nearly proportional as to render the solution indeterminate. The spectral regions used were in the violet, blue, and yellow. These were tried first because of photographic considerations; but others may prove better adapted to the requirements of the problem, and it is proposed to give the question further attention.

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[2] Seares, F. H., loc. cit.

[3] Seares, F. H., These PROCEEDINGS, **2,** 1916 (521–525).

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[5] Kapteyn, J. C., *Mt. Wilson Contr.* No. 147, p. 76, *Astrophys. J.,* **47,** 1918 (104–133, 146–178, 255–282), p. 266.

[6] Kapteyn, J. C., *Mt. Wilson Contr.* Nos. 82, 147, *Astrophys. J.,* **40,** 1914 (43–126), **46,** 1918 (104–133, 146–178, 255–282).